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Production, characterization and analysis of mechanical properties of a newly developed novel aluminium-silicon alloy based metal matrix composites

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Abstract

In this paper, a novel in situ ceramic composite consisting of Al_2O_3-SiC-C has successfully been prepared from waste fly ash material obtained from thermal power plant. The EDAX and X-ray studies have confirmed nearly complete conversion of SiO_2 to SiC by thermal reduction in a plasma reactor. Particle size ranging between 5 µm-30µm with different shape and aspect ratios are observed. Al-Si alloy based AMC are prepared with untreated and treated fly ash having 14.3% & 13.2% of volume respectively. Mechanical properties like hardness, impact energy, compression strength and tensile properties such as UTS, YS are more for AMC prepared with thermally treated fly ash in comparison to AMC prepared with untreated fly ash and Al-Si alloy.

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Keywords: Fly ash; Plasma treatement; Carbo thermal reduction; Ternary insitu cermaic composite; Al-Si alloy based MMC;

1. Introduction

During past few decades, researchers have focused on finding lightweight, eco friendly, high quality, good performance and low-cost materials (Feest 1986). In accordance with this trend, Metal matrix composites (MMC) have created growing interest among researchers and industrialists. Amongst different classes of composites, MMCs

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are the precursor. Since last twenty years MMCs have altered from a topic of scientific and intellectual interest to a material of broad technological and commercial implication (Miracle 2005). In recent years Aluminium based MMCs have received increasing attention as engineering materials because of their lightness, higher specific strength and wear resistance. Choice of a suitable combination of matrix with reinforcement materials has become an interesting area for manufacturing science in MMCs (Ashby et al.1980). Aluminium-silicon alloys, as a matrix material, are chosen for their good strength-to-weight ratio, ease of fabrication at reasonable cost, good thermal conductivity, high strength at elevated temperature, excellent corrosion resistance as well as good castability and wear resistance properties. Thus, these alloys are suitable for aerospace, automotive and military applications. Majority of eutectic or near eutectic Aluminum-silicon alloys are used to produce pistons and are, therefore, known as 'piston alloy', which provides the best overall balance of properties (Day et al.1970**)**. The traditional material such as cast iron as engine component is replaced by lightweight Al–Si alloy castings which help in savings fuel and reduces vehicle emissions .However, the main weaknesses of aluminium alloys lie in a fact that they exhibit low wear resistance and creep resistance. Therefore, ceramic particles are added to reinforce aluminium alloy matrices to overcome these problems (Pedersen et al.2006, Suresh et al.1993, Pramanik et al.2006, Zhang et al.1995,Yan and Zhang 1995,Zhang et al.1995) .Al_2O_3 and SiC powder are two commonly used reinforcing agents in Aluminium metal matrix composites (AMCs) and the addition of these reinforcements to aluminium alloys has become the subject area for research work (Sahin 2003, Hanumanth and Irons 1993).In the automotive and aircraft industries, Al_2O_3 or SiC reinforced aluminium alloy matrix composites are applied for pistons, cylinder heads, etc., where the tribological properties of the material are very important (Mostaghaci 1989, Gibson et al.1985, Dellis 1991, Rohatgi 1991, Dinwoodie 1987, Joshi et al.1995, Kocazac et al.1993). Therefore, the development of AMC is emphasized for meeting the requirements of various industries. The mixtures of hard second phase particles in the alloy matrix to produce AMC is also considered to be beneficial and economical (Chadwich and Heath 1990). Fly ash particles are potential discontinuous dispersoids used in metal matrix composites, since they are low-cost and low-density reinforcement available in large quantities as a waste by-product in thermal power plants. The fly ash contains the most important chemical constituents like SiO_2, Al_2O_3, Fe_2O_3 and CaO. It constitutes quartz, mullite, magnetite, hematite, spinel, ferrite and alumina (Rohatgi 1994). Addition of fly ash particles to Al matrix improves the hardness, wears resistance, damping properties, stiffness and reduces the density (Rohatgi et al.1997, Keshavaram et al.1984, Sobczak et al.1998). Aluminum–fly ash composites have potential applications as covers, pans, shrouds, casings, pulleys, manifolds, valve covers, brake rotors, and engine blocks in automotive, small engine and the electromechanical industry sectors. The fly ash reinforced AMCs are also termed as 'Ash alloys' (Rohatgi 1993).With the increase in the content of fly ash in Al or its alloys, the mechanical properties such as hardness, modulus of elastics, 0.2% proof stress, tensile strength, compression strength and impact strength are enhanced (Rohatgi et al.1998). It is reported that addition of fly ash in narrow range has enabled superior mechanical properties of AMC as compared to AMC prepared with wider size range fly ash particles (Rohatgi et al.1998).The ductility of the composite decreases with increase in the weight fraction of reinforced fly ash and decreases with increase in particle size of the fly ash. However, for composites with more than 15% weight fraction of fly ash particles, the tensile strength is reported to be decreasing (Rohatgi 1998).

From foregoing discussion, it is evident that use of a waste material such as fly ash in Al and its alloy is beneficial and has dispensed with the use of costly ceramic particles such as SiC or Al_2O_3 in to Al or its alloy matrices. In the present investigation a novel insitu ternary ceramic mixture composite of Al_2O_3-SiC-C is developed by carbo thermal reduction of fly ash in a plasma reactor. Addition of in situ mixture to Al alloy matrix is thought to improve properties of AMCs further. Present work will highlight results of the newly developed AMCs prepared with novel in situ ternary ceramic mixture.

2. Experimental procedure

2.1 Thermal treatment of fly ash

The waste fly ash material, obtained from thermal power plant, is screened below 240 mesh size. The average size of screened fly ash material is determined by sieve analysis. Judicious amount of activated carbon is added to the fly ash for converting SiO_2 to SiC before treating it in a plasma reactor. The total mixture is then thermally treated in a plasma reactor under neutral argon atmosphere as shown in figure-1. Untreated and treated fly ashes are then analyzed by SEM, EDS and are also characterized with XRD.

2.2 Preparation of aluminium-silicon alloy based metal matrix composite by stir casting

After cleaning Al-Si ingot, it is cut to proper sizes, weighed in requisite quantities and are charged into a vertically aligned pit type bottom poured melting furnace (Fig.2). Fly ashes are preheated to $650^oC±5^oC$ before pouring in to the melt of Aluminium-Silicon Alloy. This is done to facilitate removal of any residual moisture as well as to improve wetability. The molten metal is stirred with a BN coated stainless steel rotor at speed of 600-650 rpm. A vortex is created in the melt because of stirring where preheated fly ash is poured centrally in to the vortex. The rotor is moved down slowly, from top to bottom by maintaining a clearance of 12mm from the bottom. The rotor is then pushed back slowly to its initial position. The pouring temperature of the liquid is kept around 700^0C. Casting is made in rectangular metal mould (250x20x45 mm^3). For comparison purpose two composites are prepared, one with untreated fly ash and the other with treated fly ash.

2.3 Optical, SEM micrographic studies

Metallographic samples are cut from the central part of the ingot. The samples are examined under an optical Microscope (XJL-17). The cast AlSi-Fly Ash samples are taken for examination in SEM (JEOL-JSM, 6480LV) attached with EDX.

2.4 Mechanical properties studies

2.4.1Tensile test

The test samples (fig.3) are fabricated from Al-Si as well as from as cast composite materials. Tensile tests are conducted using Hounsefield computerized tensile testing machine (20 KN). The mechanical properties such as tensile strength, % elongation are recorded. The tensile tests results are taken from an average of three independent test results for each material.

2.4.2 Impact strength test

Impact Strength test is done in a digital pendulum impact testing machine (MECHC.S/IT30D). The standard Charpy V-notch samples (Fig.4) are used for the Charpy test.

2.4.3 Compression strength test

For comparative study of the compression behaviour of the eutectic alloy and its composites, samples of the same geometry (Ø20mmXH20mm) are taken for tests in an Universal Testing Machine. Stress values are calculated for the three materials of similar geometry, after loading 50% of their heights. The compression test results are based on an average of three independent test values of each material.

2.4.4 Hardness

Hardness test is made in a Digital display Vickers Micro hardness tester Model No.HVS-1000. The specimens used are highly finished surfaces. Micro hardness testing machine gives an allowable range of load for testing with a diamond indenter.

3. Result and discussion

3.1 Characterization of fly ash

Chemical analysis of as received fly ash (Table-1) shows presence of compounds such as Al_2O_3, SiO_2, and Fe_2O_3 as major constituents. The conversion of as received fly ash to a ternary mixture of Al_2O_3-SiC-C has been achieved in a plasma reactor (Fig.1). The conversion reaction is shown below

$$SiO_2+3C= SiC+2CO$$

Table-1: Chemical composition of Fly Ash

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
(Wt. %)	63.34	24.60	4.97	1.23	0.56	0.11	0.64

SEM micrographs show distribution of particles before and after treatment. Figs.5 (a, b) show distribution of particles for the untreated fly ash sample at two different magnifications. The corresponding SEM micrographs for treated fly ash samples are shown in Figs.5 (c, d) at the same magnification. For the untreated sample the shape of the particles are spherical with size ranging between 5µm to 30µm. For treated fly ash sample, the morphology, shape and size of particles have altered. It is observed that there are rod shaped particles with varying aspect ratios, 3-6(on an average) and number of irregular shaped particles. The change in size and morphology of particles due to thermal treatment is thought to be an important proposition since the addition of converted fly ash with such morphology and distribution is expected to enhance of mechanical properties of Al-Si based composites.

EDAX analyses are shown in Figs.6 (a,b) & 6(c,d) for both untreated and treated samples respectively. The elemental analysis of the untreated fly ash sample shows the presence of Al, Si, and O. However for treated fly ash sample EDAX analysis shows the presence of elements i.e. Si, Al, O & C.

Figs.7 (a and b) show diffraction pattern obtained from untreated and treated fly ash respectively. For untreated sample, phases identified are Al_2O_3, SiO_2, and Fe_2O_3 etc (Fig.7a). This corroborates chemical analysis shown in table.2. Fig.7 (b) shows the diffraction pattern of treated fly ash. Peaks are identified as Al_2O_3, SiC, C and SiO_2 peaks (less prominent), ensuring conversion of SiO_2 to SiC in major quantities. Together with the EDAX analysis, XRD pattern of treated fly ash (Fig.7.b) indicates that at a very high temperature under neutral atmosphere, the SiO_2 has converted to SiC during plasma synthesis, with some amount of carbon left in the product. The in situ composite thus prepared has three major constituents, i.e SiC-Al_2O_3-C. The presence of sharp carbon peaks in XRD patterns indicates the presence of unreacted carbon in the form of a crystalline phase, presumably of graphite. As a result of chemical formation of in situ phases such as SiC, Al_2O_3 & graphite, the physico chemical properties are expected to improve properties of AMC prepared with the treated fly ash.

The aluminium silicon alloy based metal matrix composites is then made by using untreated and treated fly ash. In the present investigation, it is anticipated that both the composites i.e Al-Si with untreated fly ash and treated fly ash will have the same vol% of the dispersed phases. However, within the experimental limitation, it was possible to have14.2 and 13.3 vol% of particulates in the untreated and treated composites respectively

3.2 Preparation of Al-Si alloy based metal matrix composite.

Matrix used: Eutectic Al–Si (LM6) alloy.
Reinforcement used: As received fly ash (untreated) and thermally treated fly ash.
The chemical analysis of the alloy is given in Table 2

Table 2. Composition of Al-Si alloy [wt. %] designated as a base alloy

Si	Co	Fe	Cu	Mn	Ti	Zn	Ni	Sn	Cr	Ca	V	Al
12.2491	0.0174	0.4353	0.0800	0.1601	0.0672	0.0944	0.0264	0.0632	0.0199	0.0082	0.0146	86.7654

3.2 Microstructural studies.

Figs.8 (a, b and c) show optical micrographs for Al-Si Alloy, AMCs prepared with untreated and treated fly ash. The Volume fraction is measured to be 14.2% and 13.3% respectively. There is not much difference in volume % in the microstructure. The distribution of particles in the microstructure is seen to be uniform. On etching fine grain structures are observed.

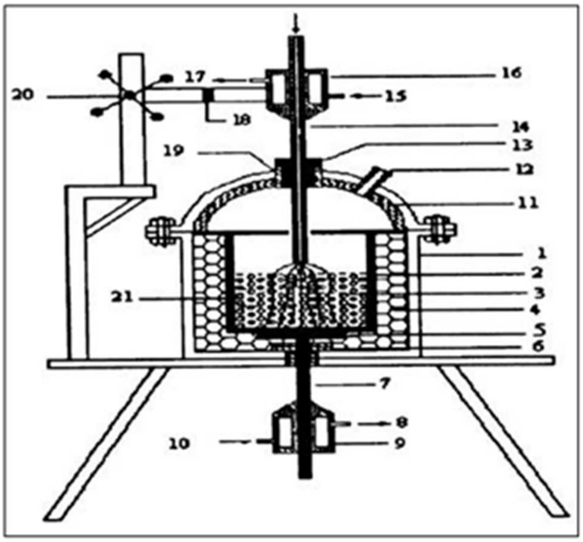

Fig.1 Schematic view of the plasma rector (1.M.S. Casing.2. Graphite crucible.3.Graphite crucible.3.Plasma. 4. Bubble alumin.5 Graphite base. 6. Alumina bush.7. Bottom electrode (graphite) 8.water outlet 9. Copper connector, 10. Water in 11. Magnesia lining. 12. Exhaust. 13. Graphite bush, 14.Top electrode (graphite), 15. Water in 16. Copper connector 17. Water out, 18 Electrical Insulation 19. Alumina bush. 20. Rack and pinion and 21. Charge)

Fig.2. Bottom pouring furnace

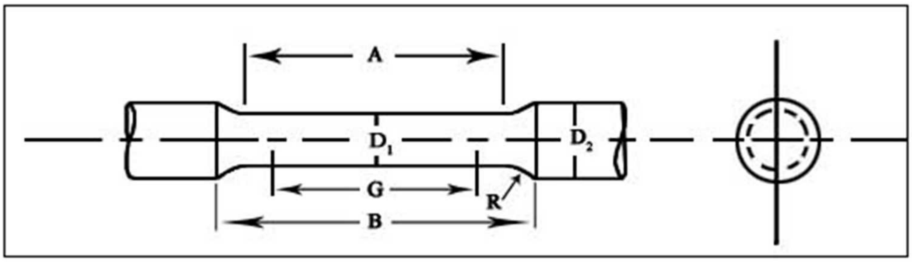

Fig.3 Tensile strength sample

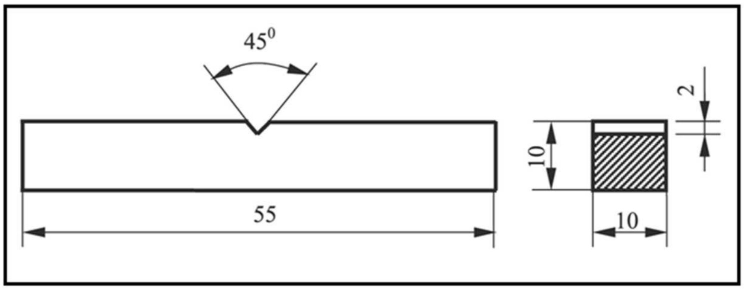

Fig.4 Charpy V- notch sample

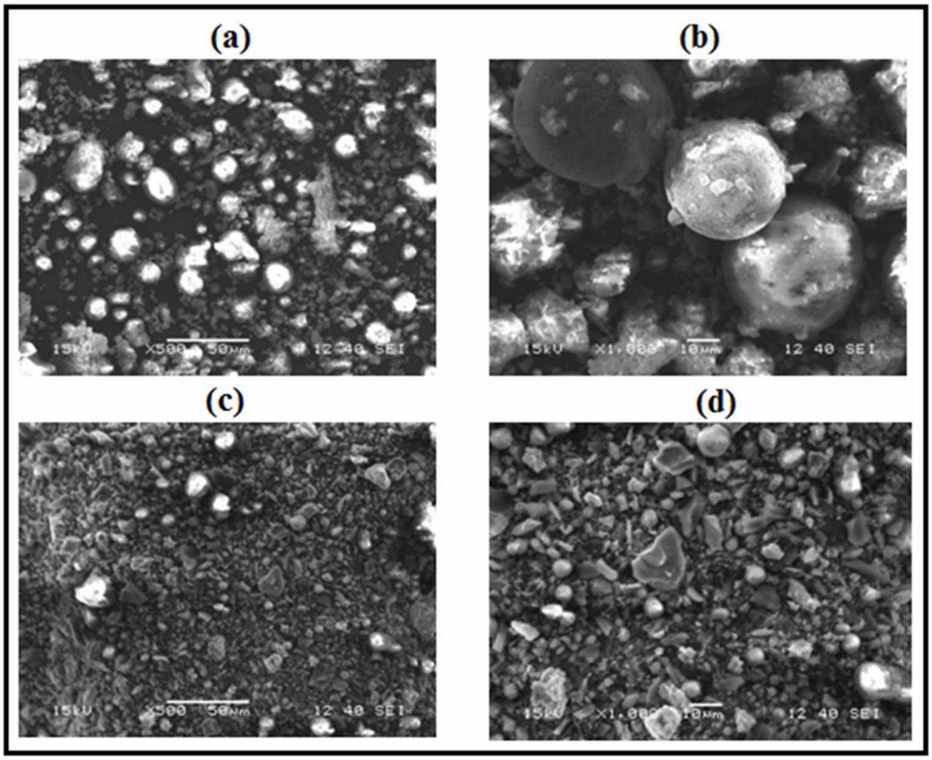

Fig.5 SEM Micro graph of fly ash (a) Untreated Fly ash at 500X (b) Untreated Fly ash at 1000X (c) Plasma Treated Fly ash at 500X (d) Plasma Treated Fly ash at 1000X

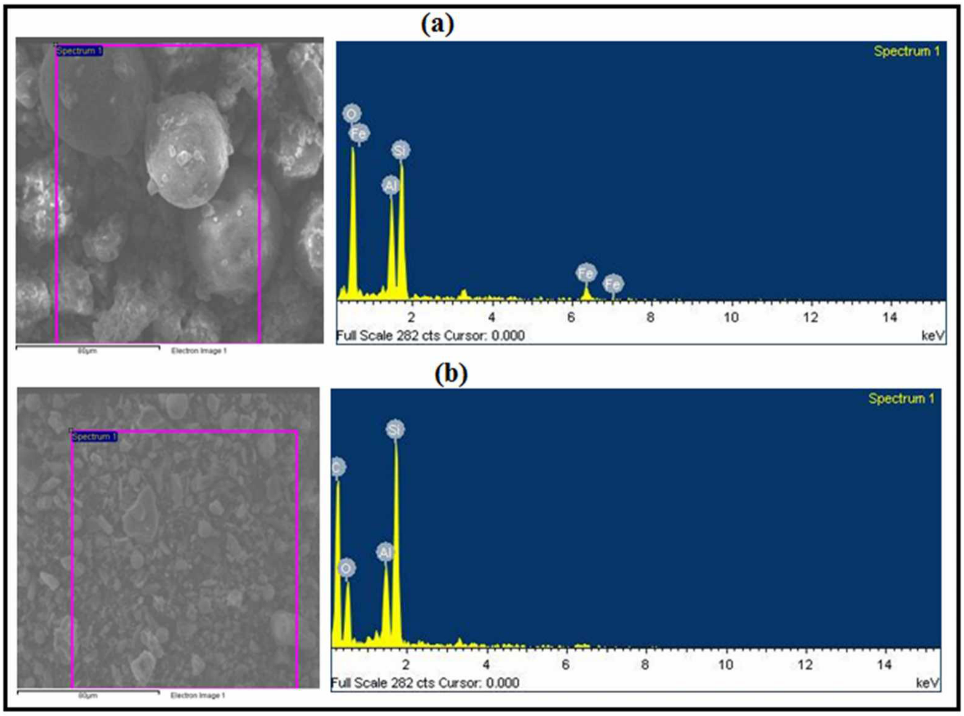

Fig.6 (a) SEM and EDX analysis of UFA, (b) SEM and EDX analysis of TFA

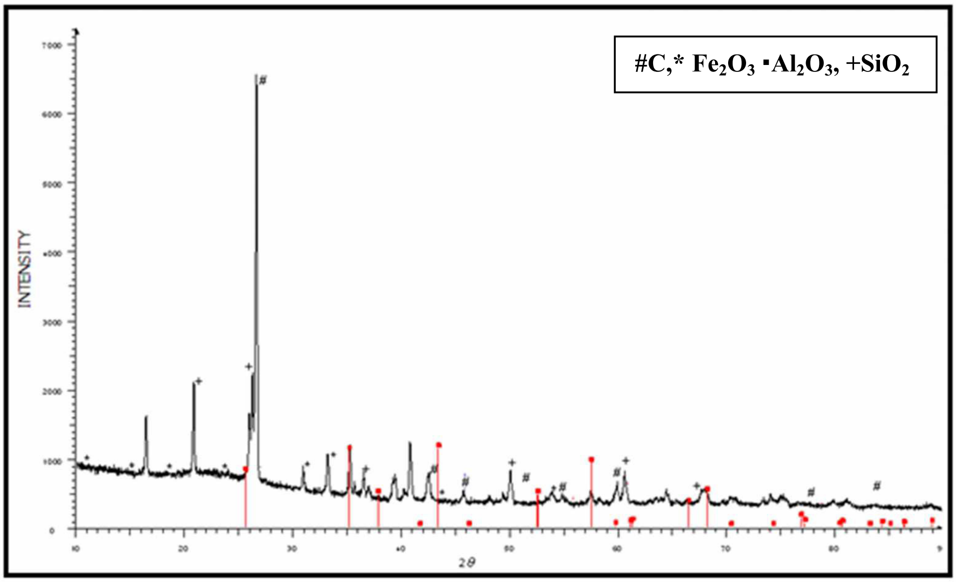

Fig.7 (a) XRD pattern of untreated fly ash

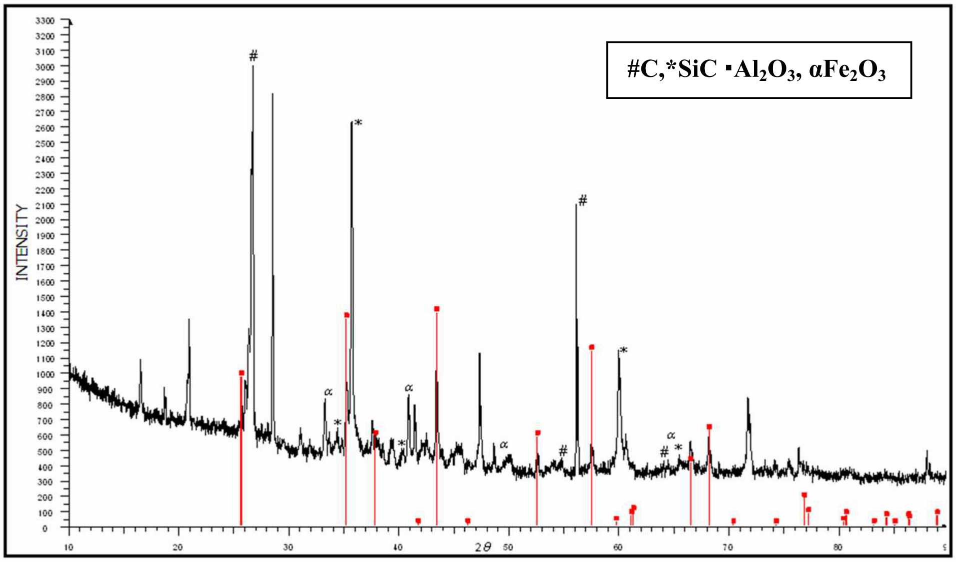

Fig.7 (b) XRD pattern of Plasma treated fly

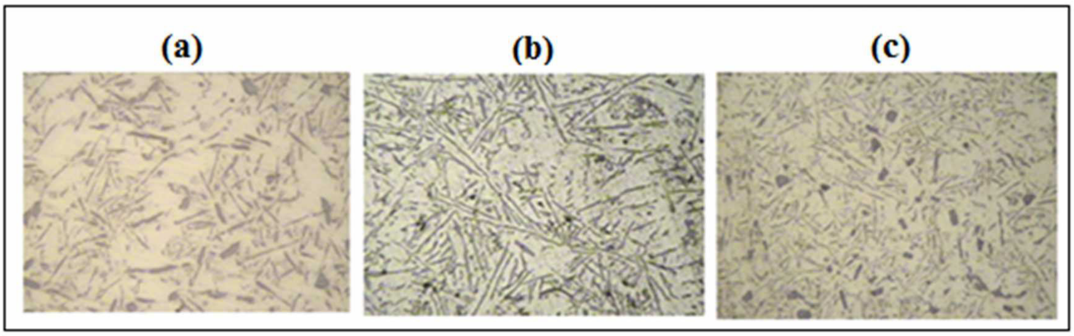

Fig.8 Optical Micro graphs (a) Al-Si Alloy, (b) AMC (Untreated Fly Ash), (c) AMC (Treated Fly ash)

3.3 Mechanical properties

Table.3 shows hardness values for three materials i.e Al-Si (Eutectic), AMC with untreated fly ash (14.2%) and AMC with treated fly ash (13.3%). The average value of hardness recorded is found to be the highest for AMC prepared with the treated fly ash. The tensile properties are measured and shown in table.4. Charpy Impact test is done for the three materials and results are shown in table.5. It is noted that the amount of energy absorbed by AMC prepared with treated fly ash is higher in compression to other two materials i.e Al-Si alloy and AMC prepared with untreated fly ash. Result of compression test table.6 has also shown the highest strength value for AMC prepared with treated fly ash in comparison to Al-Si alloy and AMC prepared with untreated fly ash. The largest value obtained under static as well as dynamic test conditions for AMC prepared with treated fly ash material is attributed to the microstrural changes, caused due to carbo thermal reduction and formation of SiC from SiO_2. The insitu structure has enabled improvement in the properties because of change in morphology of the microstructure i.e spherical shape to rod shaped as well due to fineness of the reinforcing particles.

Table 3. Hardness test of the specimens

Sample No	Sample name	Trial-1	Trial-2	Trial-3	Mean in HV
01	Al-Si	64.50	62.50	62.75	63.25
02	AMC(UT)	67.27	69.90	67.58	68.25
03	AMC(T)	75.67	73.80	76.74	75.40

Table.4 Tensile Test of the specimens

Sample No	Sample name	Trial-1	Trial-2	Trial-3	Mean in N/mm^2
01	Al-Si	143.8	144.6	143.6	144.0
02	AMC(UT)	162.6	162.7	162.9	162.7
03	AMC(T)	212.9	212.8	213.2	212.9

Table.5 Impact strength of the specimens

Sample No	Sample name	Trial-1	Trial-2	Trial-3	Mean in Joule
01	Al-Si	0.5	0.5	0.5	0.5
02	AMC(UT)	2.5	2.4	2.6	2.5
03	AMC(T)	2.4	2.9	2.8	2.7

Table.6 compression strength of the specimens

Sample No	Sample name	Trial-1	Trial-2	Trial-3	Mean in N/mm^2
01	Al-Si	461	463	462	462
02	AMC(UT)	479	478	477	478
03	AMC(T)	492	491	490	491

4. Conclusion

The major conclusions drawn from the present investigation are as follow:
1. A novel in situ ceramic composite consisting of Al_2O_3-SiC-C has successfully been prepared from waste fly ash Material, obtained from thermal power plant.
2. Flay ash containing SiO2 is converted to SiC in major quantities by thermal reduction.
3. SEM, EDAX and XRD analyses have confirmed successful conversion of SiO_2 to SiC in major quantities with some unreacted C, presumably of graphite.
4. AMCs prepared with untreated and treated fly ash have 14.2 %and 13.4% volume fly ash in the matrix, respectively.
5. Mechanical properties such as hardness, tensile properties (UTS), impact strength and compression strength are more for AMC prepared with treated fly ash in comparison to the other two materials i.e. AMC prepared with untreated fly ash and Al-Si alloy.

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